GRAIN SIZE ALONG TWO GRAVEL-BED RIVERS: STATISTICAL VARIATION, SPATIAL PATTERN AND SEDIMENTARY LINKS

STEPHEN RICE[1]* AND MICHAEL CHURCH[2]

[1]*Department of Geography, Loughborough University, Loughborough, Leicestershire, LE11 3TU, UK*
[2]*Department of Geography, The University of British Columbia, Vancouver, BC, Canada, V6T 1Z2*

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ABSTRACT

A new set of field data facilitates a detailed analysis of variations in bed material grain size within two confluent gravel-bed rivers in northeastern British Columbia, Canada. A preliminary assessment of grain-size variability establishes a basis for examination of the spatial pattern of grain-size change. Standard ANOVA techniques are inappropriate because individual samples have unequal variances and are not normally distributed. Alternative tests for homoscedasticity and comparison of means are therefore utilized. Within-site, between-sample variability is not significant. The grain-size distributions that were obtained at individual sites are therefore representative of the depositional environments that were sampled. In both rivers mean grain size does vary significantly between sites and there is therefore a basis for examining the data for spatial patterns such as downstream fining.

Textural variations along the two rivers studied here are complex and show negligible overall fining (in over 100 km). This is the consequence of a large number of tributary inputs and non-alluvial sediment sources which are the legacy of Late Pleistocene glaciation. The identification of lateral sources like these is fundamental for understanding textural changes within rivers. The sedimentary link (a channel reach between significant lateral sediment inputs) provides a means of isolating fluvial maturation processes (abrasion and sorting) from contingent lateral inputs. Strong fining trends are apparent in most links and classification of grain-size measurements according to their location within particular links greatly improves the statistical explanation of textural variation. Identification of sedimentary links provides a means of applying models of fluvial fining processes, so isolation of link networks will aid the development of basin-scale models of textural variation.

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INTRODUCTION

The spatial variation of bed material grain size along gravel-bed rivers has been a long-standing interest of fluvial geomorphologists and sedimentologists. Empirical investigations have focused on the role of textural variation in controlling river channel morphology and longitudinal form (Sternberg, 1875; Mackin, 1948; Pizzuto, 1992), on the causes of variation, including abrasion (Kuenen, 1956; Kodama, 1994), sorting (Russell, 1939; Brierley and Hickin, 1985; Ferguson *et al*., 1996), weathering (Bradley, 1970), geomorphic history (Shaw and Kellerhals, 1982), tributary inputs (Miller, 1958; Knighton, 1980) and hillslope–channel coupling (Krumbein, 1942; Rice and Church, 1996a), and on palaeoenvironmental reconstruction (Schlee, 1957; Mayer *et al*., 1984).

Theoretical arguments and empirical evidence suggest that grain-size distribution parameters decline systematically in a downstream direction, particularly between tributary junctions in the absence of coupling with non-alluvial sediment sources (Sternberg, 1875). Two processes – particle abrasion and selective transport – are widely recognized as the dominant causes of this downstream fining. Abrasion is a summary term for a range of wearing processes, such as chipping, grinding and breakage, which mechanically reduce the size of individual clasts (Kuenen, 1956). Selective deposition or, simply, sorting refers to the differential transport of

Correspondence to: S. Rice
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grains as a function of their size, whereby smaller, more mobile clasts are supposed to 'outrun' their larger counterparts (Russell, 1939).

Considerable progress has recently been made in developing physically realistic models of these processes (Stelczer, 1981; Parker, 1991; Hoey and Ferguson, 1994; Paola and Seal, 1995; Cui *et al*., 1996). The complexity of the mechanics involved has necessitated an initial focus on single-source situations (Hoey and Ferguson, 1994) and relatively simple gradients of downstream fining. Such trends certainly occur within individual reaches, and the pattern in general characterizes bed material throughout large fluvial systems. However, patterns of textural change are more complex over considerable distances in many river channels where, because of multiple sediment sources, fining processes account for only part of the observed variation. Troutman (1980) and Pizutto (1995) have made initial attempts to incorporate sediment mixing at confluences into models of textural change.

Sternberg (1875, p. 494), in his seminal work, noted that tributaries will only by chance introduce material similar to that in the mainstem, while Mackin (1948, p. 483) asserted that 'calibre of load does not vary systematically in graded streams joined by tributaries'. Miller (1958) suggested that coarse sediment supplied by tributaries was in part responsible for the grain-size fluctuations he observed along streams in the Sangre de Cristo Mountains of New Mexico. Subsequent studies have identified disruptions in downstream maturation in response to sediment inputs at confluences (Church and Kellerhals, 1978; Knighton, 1980; Ichim and Radoane, 1990; Brewer and Lewin, 1993), at tributary fan contacts (Bradley *et al*., 1972; Dawson, 1988), and downstream from outcrops of non-alluvial materials, such as glacial drift and bedrock (Bradley *et al*., 1972; Werritty, 1992).

We refer to such inputs as *lateral sediment sources* because they inject material which has characteristics established independently of processes operating longitudinally within the recipient channel. Particularly large or dissimilar lateral sources delimit a series of distinct reaches, within which sorting and abrasion processes systematically modify the redefined throughput population. In turn it has been demonstrated that a series of discrete size–distance relations are best suited to the description of changes in bed material texture along a fluvial system. For example, a series of negative exponential models, each delimited by clear breaks at tributary junctions, significantly reduced unexplained variation along the Peace River in British Columbia (Church and Kellerhals, 1978), various upland streams in England (Knighton, 1984), and part of the Sunwapta River in Alberta (Dawson, 1988).

The present paper analyses the spatial changes in grain size which occur along two upland gravel-bed rivers in northeastern British Columbia, Canada. The work is distinguished from many previous field studies by the scope and resolution of the sampling programme. These distinctions are underlain by a conviction that a better appreciation of the circumstances within which fining processes actually operate requires more detailed sampling than has been customary.

Identifying which of many potential sources have a persistent downstream influence on bed material texture is not straightforward. Beyond general references to relative tributary size, sediment load and influent sediment calibre, there are no existing theoretical or empirical guidelines for making *a priori* distinctions. Consequently, one must focus on the textural information and isolate the important lateral sources on the basis of their effect rather than their cause. This procedure hinges on the identification of *discontinuities*, that is, on displacements or steps in the grain-size signal that reflect a hiatus in downstream textural modification (the 'sediment character jumps' of Brewer and Lewin (1993)), and is complicated by the spatial variability of bed material texture. This paper is concerned with the identification of the lateral sediment sources along the two rivers, the improvement in explanation which they afford, and the implications they have for modelling textural change in fluvial systems.

As a preliminary exercise, we consider two questions. How representative of the depositional environments that were sampled are the grain-size distributions that were obtained at individual sites? Are the variations in grain size between sites significantly greater than those at a site? If between-site variations are not significant, there is no basis for seeking a relation between grain size and location. Standard analysis of variance techniques are appealing because of their widespread use and straightforward application. However, not all sedimentary grain-size distributions meet normality and homogeneity conditions for robust ANOVA. This problem afflicts the surficial fluvial deposits examined here, even after transformation onto the phi scale. So, methods for comparing the central tendency of non-normal, heteroscedastic grain-size distributions are employed.

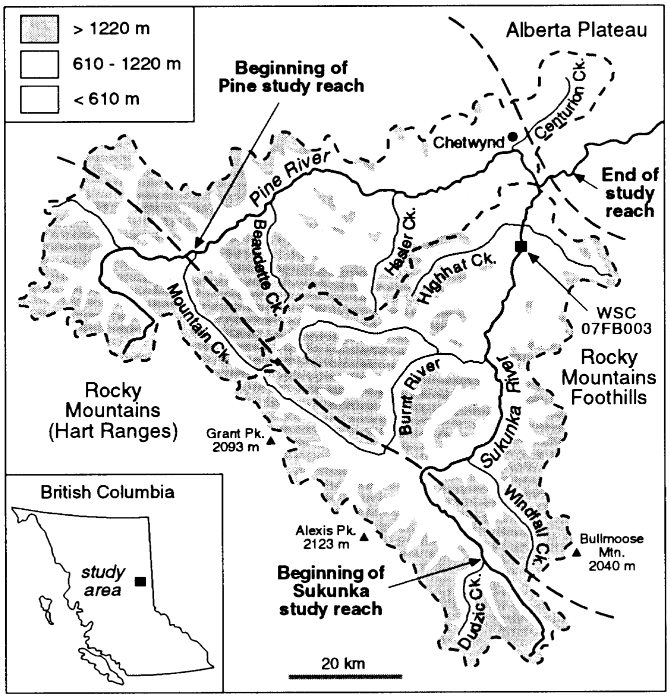

Figure 1. Study area

STUDY AREA

Pine and Sukunka Rivers drain the eastern flank of the northern Rocky Mountains and flow east and north toward the Alberta Plateau (Figure 1). Upstream of their confluence near the town of Chetwynd they have drainage areas of approximately 2500 and 2750 km^2 respectively. At hydrometric station 07FB003 (Water Survey of Canada), located near the mouth of Sukunka River, mean flow is 54 $m^3 s^{-1}$ and the mean annual flood is 480 $m^3 s^{-1}$. Peak daily discharge for the 13 year period of record is 705 $m^3 s^{-1}$. Maximum flows occur in May and June in response to river-ice break-up and regional snowmelt.

With the exception of the upper Sukunka, both study reaches lie within the foothills belt where the rivers flow across the dominant northwest–southeast structural trend. Relief declines from about 900 m in the headwaters to about 600 m near the confluence and the peaks of the continental divide (*c.* 2100 m) are replaced by an undulating plateau (*c.* 1000 m) interspersed with anticlinal cuestas and escarpments. Intensely folded and thrust-faulted Palaeozoic rocks in the mountains give way to successively younger Mesozoic rocks in the foothills. Shale, sandstone and quartzite lithologies dominate both basins. Within the study reaches, each of which is about 100 km long, Sukunka River drops approximately 275 m and Pine River approximately 150 m, to give average channel slopes of approximately 0·0025 and 0·0014 respectively.

Glaciation has left a legacy of morainal, glaciofluvial and glaciolacustrine deposits within both river valleys; along with tributaries, Holocene fans and colluvial deposits, these are important sources of clastic sediment for the contemporary rivers. Although the present channels are intermittently coupled to non-alluvial sediment sources, they have developed extensive alluvial deposits and, in places, the main channels migrate over alluvial accumulations several kilometres wide. Both rivers have a wandering planform characterized by irregular sinuosity, few vegetated islands, and complex arrangements of gravelly point, medial and lateral bars. Active (unvegetated) channel width is approximately 40 m at the head of each reach and increases irregularly to about 100 m near their confluence.

Using aerial photographs and field observations, the landforms and surficial materials adjacent to both study reaches have been mapped. Figure 2 illustrates the principal features of the surficial geology, which are

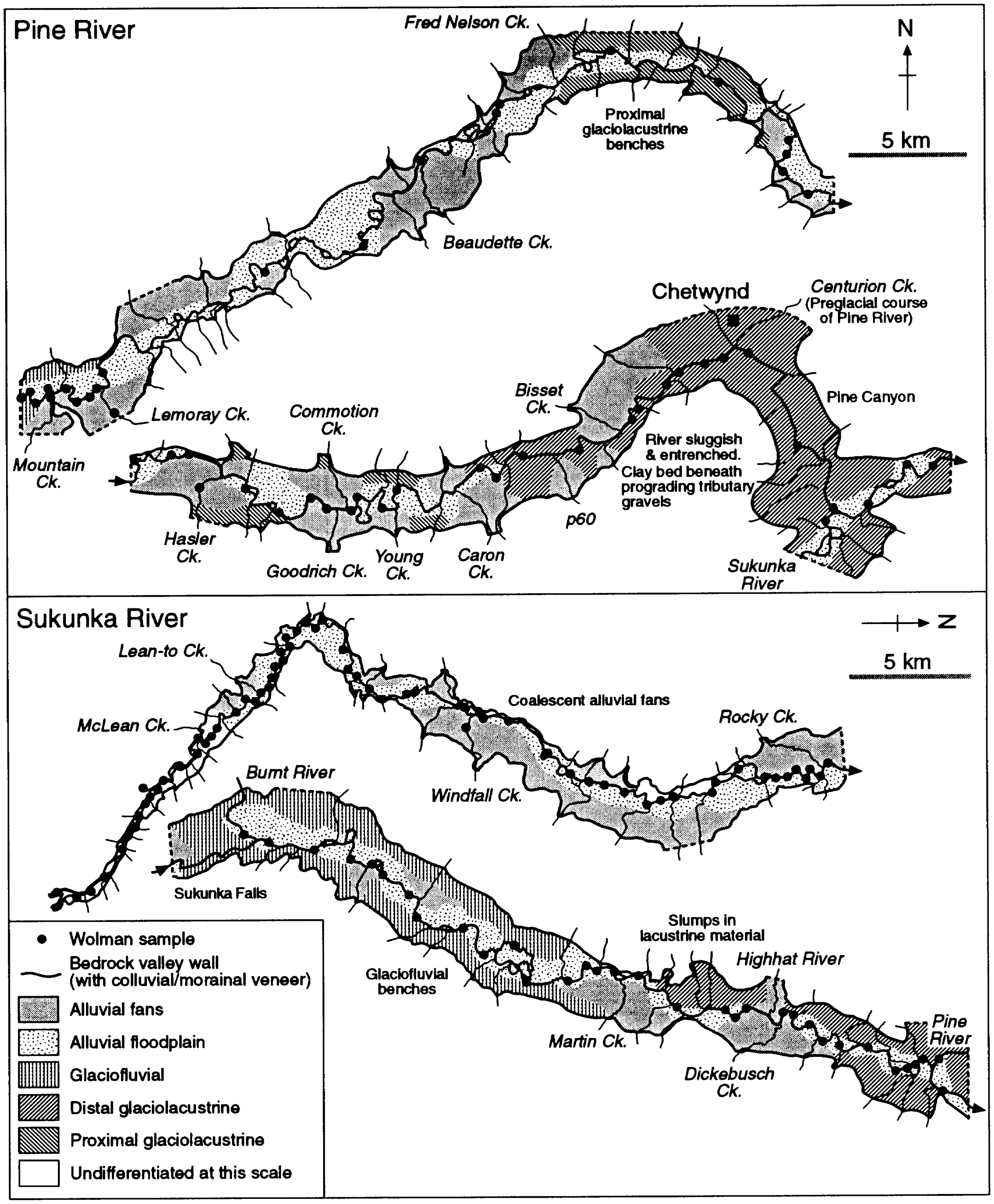

Figure 2. Simplified surficial geology and landforms of the Pine and Sukunka River valleys showing location of Wolman sample sites

described in detail elsewhere (Rice, 1996), and shows the tributaries indicated on 1:50000 National Topographic Survey (NTS) mapping. There are 79 tributaries to the Sukunka and 76 to the Pine.

SEDIMENT SAMPLING METHODS

Site selection

A river bed presents a variety of transporting and trapping conditions to migrating sediment. From a heterogeneous mixture, individual grains tend to settle in positions consistent with their size and shape and, as a

result, substantial local sorting is evident in gravel-bed rivers (Bluck, 1982). This is apparent in the contrasting textures of pools and riffles (Keller, 1971; Milne, 1982), on simple bars with relatively coarse heads and fine tails (Bluck, 1971; Smith, 1974), and within more complex assemblages of bar units which reflect a number of depositional and erosional events. Observations (cf. Mosley and Tindale, 1985; Wolcott and Church, 1991) indicate that the textural variability across an individual bar often exceeds that observed between similar depositional environments separated by distances of many kilometres.

Therefore, to study longitudinal variations in texture, care must be taken to sample consistently material which is associated with a particular riffle/bar-scale sedimentary environment. Local depositional variations are otherwise likely to be confounded with the longitudinal pattern. This is not equivalent to collecting samples from the same relative position (e.g. the bar head) because locations of maximum turbulence, lowest velocity or minimal roughness, for example, are not located consistently. Thus, Dawson (1982) found that textural variation within braid bars is not systematic.

The coarsest active material present in the bed has been the focus of previous fining studies (for example, Church and Kellerhals, 1978), and is also considered in this study. There are at least four reasons for this choice: the coarsest material is most easily distinguished amongst all the material on the bar; it has potentially the largest range in signal (hence the greatest resolution) along the river; it may be related most directly to suggested controlling hydraulic mechanisms (e.g. competence and abrasion); and it is generally considered to exert the greatest influence on channel roughness. At bars selected for sampling, a reconnaissance of the surface was conducted and the sampling site was located in that unit which consisted of the coarsest active material found. Not surprisingly these high energy sites were generally closer to the channel and the bar head than to the bank or bar tail. The scale of the study precluded adoption of special measures which would be necessary for consistent sampling underwater, but sampling was conducted at stages which allowed access to active bed material. Inactive sediment, indicated by a substantial cover of moss or lichens, was avoided because it may bear little relation to the current river regime. Sites were located on emergent mid-channel, lateral and point bars (in that order of preference) which were not affected by the presence of large organic debris.

Wolman sampling

Wolman (1954) introduced grid-by-number surficial sampling whereby a sample consists of clasts picked by hand from the surface. The primary problem with the method is its inability to represent fine materials because it is difficult to identify and handle small clasts. Wolman suggested that particles between 2 and 4 mm are the smallest that can be handled in the field. Areal sampling techniques involve measurement of all the grains exposed within a given area of the bed, and therefore capture finer material (Diplas and Sutherland, 1988). However, they are more time-consuming than Wolman sampling and, in cobble-gravels, typically underestimate the coarsest material present because practical techniques do not cover a sufficient area.

Along Pine and Sukunka Rivers very little fine material is exposed within the coarse, active units chosen for sampling. This suggests that Wolman sampling is appropriate. Practical experience and convention suggest that particles larger than 8 mm can be recovered without bias, and 8 mm was therefore employed as a practical truncation limit. This means that the study is a study of gravel variability *sensu stricto*. It is therefore convenient (following Parker and Andrews, 1985) to express grain-size measurements and statistics in psi, $\vartheta = \log_2(D)$ units, where D is a grain-size measurement in millimetres ($\vartheta = -\Phi$, the customary sedimentological unit of grain size).

Performance assessments of grid-by-number sampling (Wolman, 1954; Brush, 1961; Penning-Rowsell and Townshend, 1978; Hey and Thorne, 1983; Mosley and Tindale, 1985) have focused almost exclusively on establishing the population mean or median, and indicate that 60 to 100 particles are needed to consistently estimate either. Using the bootstrap technique, Rice and Church (1996b) determined absolute percentile standard errors across the entire distribution of sizes. They suggest that, as a general guideline, additional gains in precision are not sufficient to warrant the field effort involved in collecting samples of more than 400 clasts. In this study a sample size of 400 was therefore adopted. A 400-stone criterion was also suggested by Fripp and Diplas (1993). Actual sample size varied in minor degree due to site conditions.

Samples were collected at 90 sites on the Sukunka mainstem and at 49 sites along the Pine (Figure 2). Sampling density varies along the two rivers because of differences in accessibility. At each site a grid was laid

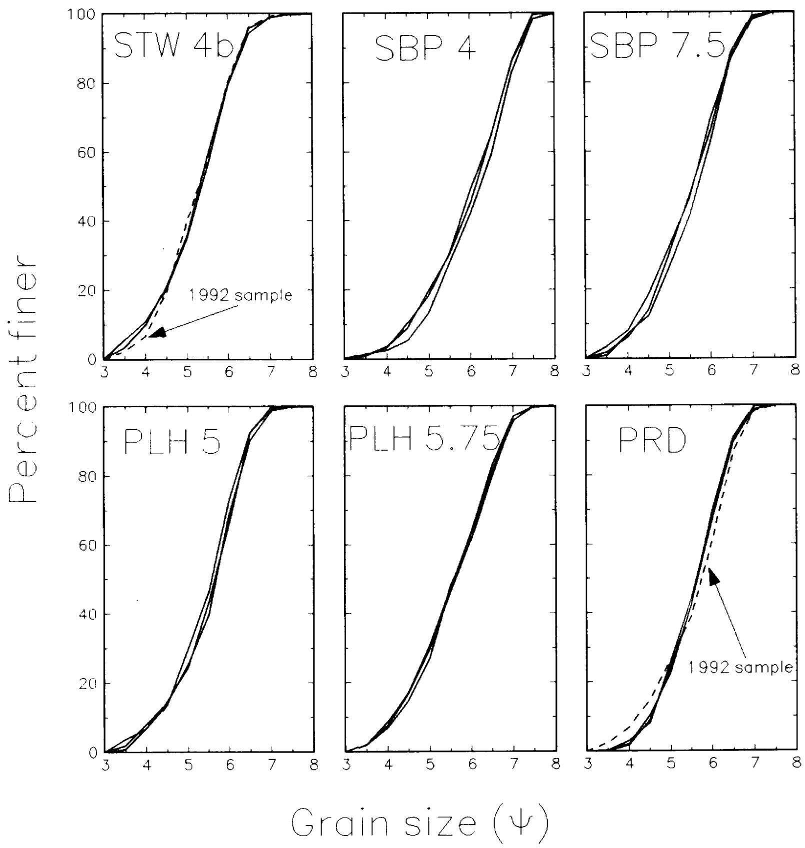

Figure 3. Replicate Wolman samples collected at six sites

out on the coarsest active unit that could be identified. Grid dimensions varied with the shape of the unit but were designed to ensure a distance of at least two maximum particle diameters between sampling points and thereby assure the independence of individual observations. Typically a 0·5 or 0·75 m interval was employed. Particles beneath the grid intersections were sorted using half-psi templates.

To assess within-site sampling error, three or four replicate samples were collected at six sites (Figure 3). Different sites were sampled in 1992 and 1993, which introduces the possibility that an unspecified temporal effect could confound the spatial variations under examination. However, two of the replicate sets (STW4b and PRD) include samples collected in 1992 and 1993 and confirm that there was very little change in the bed between field seasons (Figure 3). Significant temporal changes presumably occur in response to floods capable of mobilizing large portions of the bed. Between sampling periods the maximum daily discharge at hydrometric station 07FB003 was 383 m^3 s^{-1}, which represents a return period of only 1·4 years. An estimate of local dimensionless shear stress for peak discharge is $\tau_* = 0{\cdot}029$, which is at the lower limit of values typically associated with initial motion in natural gravel beds. As the replicate evidence suggests, it is unlikely that general movement occurred between sampling periods. This result is consistent with observations of short-term grain-size stability on gravel bars in the River Tulla, Scotland, and Markarfljot sandur, Iceland, by Bluck (1982).

Lateral, point and medial bar types were sampled at different sites, raising the additional issue of whether texture (at least within the coarsest active units) is systematically related to bar type. Standard ANOVA indicates, however, that there is no significant difference in mean grain size between bar types ($p = 0{\cdot}312$).

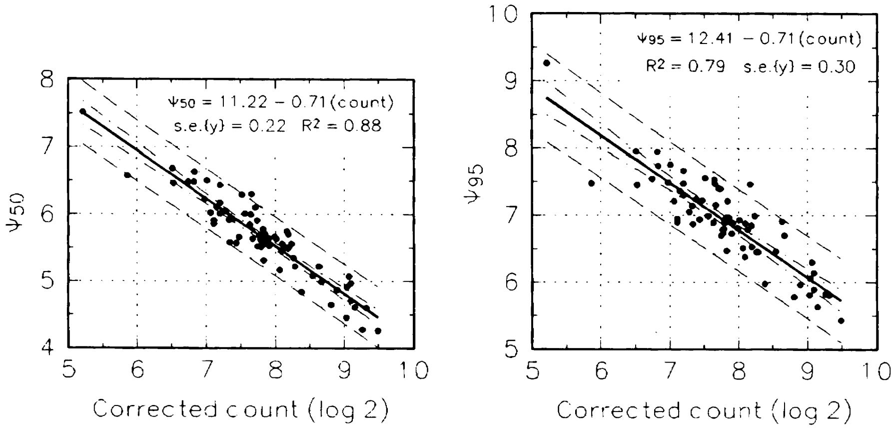

Figure 4. Photographic calibration models for Ψ_{50} and Ψ_{95}; 95 per cent confidence limits for the regressions and individual predictions are shown

Photographic sampling

In order to improve sampling resolution while minimizing field time, a photographic technique (Church *et al.*, 1987; Rice and Church, 1996a) was used to obtain summary grain-size information at an additional 51 sites on Sukunka River and 39 sites on Pine River. At 69 sites where Wolman samples were collected, a $0{\cdot}25\,m^2$ quadrat was placed at random within the Wolman grid and photographed. The number of grains exposed within each photographed quadrat was counted. A clast was counted only if more than 50 per cent of it lay within the quadrat. Material finer than $3{\cdot}0\Psi$ (8 mm) was not included in the count, since it is not possible to isolate individual grains accurately below this size. An estimate was made of the fraction of the image which was obscured by shadow, P_{sh}, and which showed material smaller than 8 mm, P_8. Counts were then corrected for this loss of area to give the count which would be expected in the absence of fines or shadow. Photographs with $P_{sh}+P_8>0{\cdot}15$ were excluded from the analysis.

Least-squares linear regression was used to model the relations between Ψ_{50} and Ψ_{95}, and the corrected count. Both are significant (Figure 4). Individual predictions might vary by approximately $\pm 0{\cdot}45\Psi$ for Ψ_{50}, and approximately $\pm 0{\cdot}63\Psi$ for Ψ_{95}, at the 95 per cent confidence level. These errors are not trivial, but they are acceptable given the aim of obtaining useful information with minimal field effort.

GRAIN-SIZE VARIATIONS

The representativeness of within-site samples and the significance of between-site variations were assessed using the Wolman samples (Figure 5). Half-psi frequency counts based on large samples provide accurate estimates of mean grain size $\overline{\Psi}$ variance s^2, skewness α_3 and kurtosis α_4 at each site.

Analysis of grain-size variations

Church and Kellerhals (1978) addressed these issues in their study of grain-size variations along Peace River in British Columbia (which is the trunk stream, with similar topography and geology, into which the study rivers drain). A nested analysis of variance model was then used to compare within-sample grain-size measurements with replicated measurements at the same site and to compare between-site differences with the variance typical at a site. Similar grain-size analysis was conducted by Dawson (1988) on Sunwapta River in Alberta, and by Huddart (1994) on Öraefi sandur, Iceland. The use of a nested variance model, and indeed any ANOVA technique which is based on the calculation of F-statistics, is predicated on a number of assumptions about the measurements involved. The three principal requirements are that samples be normally distributed, have equal variances, and be independent.

Cliff and Ord (1981) highlight the potential for spatial autocorrelation in geographical data. Sorting at a variety of scales means that there is the potential for non-independence amongst grain-size measurements

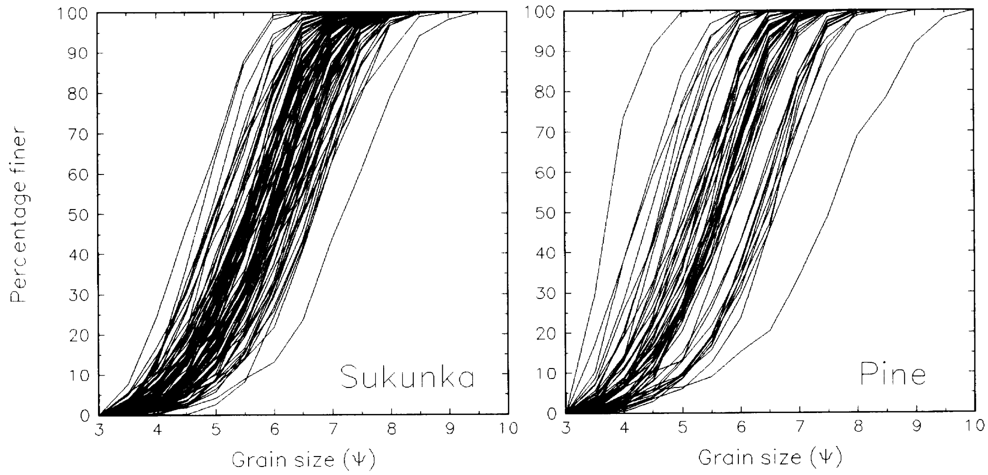

Figure 5. Cumulative grain size curves for the Wolman samples

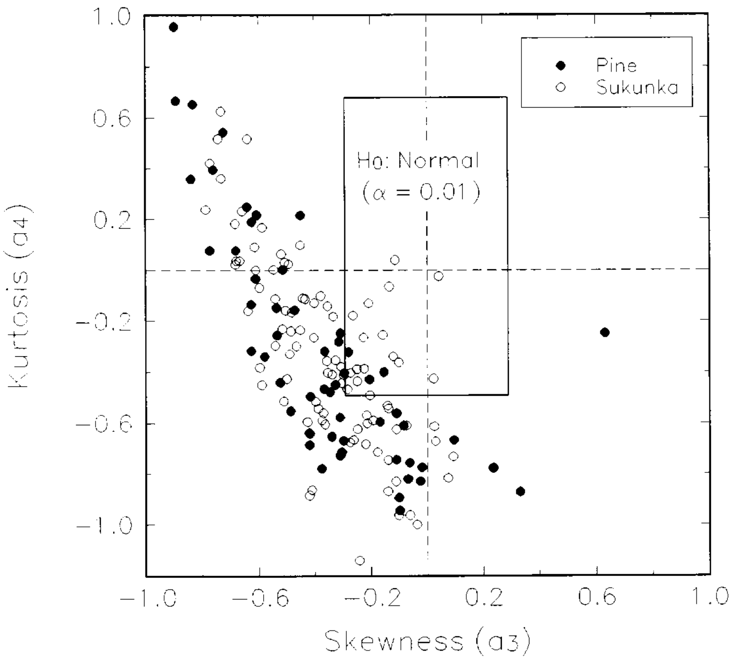

Figure 6. Skewness, kurtosis and non-normality of Pine and Sukunka Wolman samples. Note that on the psi scale negative skewness indicates a tail in the finer fractions and a shift toward coarser material

carried out across a bar surface. Two aspects of our sampling procedure are intended to safeguard against this. First, a critical distance was maintained between sampling points (the grid-line spacing) such that individual observations are supposed to lie outside the area of hydraulic influence of adjacent sampling points. On the basis of field experience and convention, a grid spacing of at least two times the diameter of the largest particle present was used. Second, the spatial extent of sampling units was carefully defined and the texture within each unit carefully examined in an effort to preclude noticeable textural gradients across the unit. We are confident that our samples represent $n \approx 400$ pieces of information at each site and that sample standard errors are, therefore, unbiased.

Box (1953), Tan (1982) and others have assessed the robustness of ANOVA procedures under non-normality. Their general finding is that non-normality is not a serious problem, especially if sample

Table I. Brown–Forsythe tests of homoscedasticity for Pine and Sukunka Wolman samples

	k	N	A	B	V=A/B	$F_{(\alpha=0\cdot001)}$
Sukunka	96	37954	4·0462	0·2862	14·14	1·54
Pine	56	21421	4·3336	0·2577	16·82	1·71

k is the number of samples, N is the total number of observations, A is the variance of the spread of observations between samples, B is the variance of the spread within samples, and $V = A/B$. Where $V > F_{(\alpha)}$ reject H_0 of no significant difference

Table II. Within-site, between-sample variability. Equality of sample means at six replicate sites

Site	Number of replicates, k	W	X	C	$\chi^2_{(\alpha=0\cdot05)}$	$\chi^2_{(\alpha=0\cdot10)}$
PLH 5·75	3	1342·098	5·534	1·00	5·99	4·61
PRD	4	2716·828	5·571	0·49	7·81	6·25
PLH 5	3	1653·835	5·484	2·99	5·99	4·61
SBP 4	3	1274·827	6·001	5·76	5·99	4·61
SBP 7·5	3	1539·207	5·515	4·70	5·99	4·61
STW 4b	3	1627·721	5·244	0·06	5·99	4·61

Where $C > \chi^2_{(\alpha)}$ reject H_0 of no significant difference ($>\chi^2_{(\alpha)}$ is the 1–α percentile of the χ^2 distribution with k–1 degrees of freedom)

distributions are of approximately the same shape. Violating the assumption of equal variances (homoscedasticity) is, however, problematic. Using a narrow range of variances, $\Theta = \sigma^2_{max}/\sigma^2_{min} \leq 3$, Box (1954) reported that variance inequality does not seriously affect the behaviour of an F-test when samples are of approximately equal size. In contrast, Monte Carlo simulations for $\Theta^2 \leq 25$, reveal that actual Type I errors may be several times the nominal level, even if samples are of a similar size (Brown and Forsythe, 1974a; Wilcox, 1987; Dijkstra, 1988). Values of Θ^2 for the Wolman samples (psi data) are $\Theta_s{}^2 = 3\cdot9$ (Sukunka) and $\Theta_p{}^2 = 9\cdot3$ (Pine), exceeding what could be considered tolerable heteroscedasticity.

Furthermore, Wilcox (1987) suggests that the F-test becomes increasingly sensitive to heteroscedasticity as the number of samples being compared increases. Comparisons between a large number of samples are to be made. There is therefore every indication that a standard ANOVA procedure based on the use of F-statistics is inappropriate. However, Θ^2_s and Θ^2_p utilize only the two extreme sample variances. Before abandoning standard ANOVA techniques, we assessed the homoscedasticity of the grain-size samples using a more rigorous method.

The standard test for homoscedasticity, after Bartlett (1937), was used by Dawson (1988) and Huddart (1994) to assess the variance equality of their respective grain-size samples. Bartlett's test is highly sensitive to non-normality (Box, 1953) and it is therefore necessary to assess the normality of the psi data prior to using the test. For a symmetric distribution $\alpha_3 = 0$, and for a normal distribution $\alpha_4 = 0$. Coefficients are plotted in Figure 6 for all Wolman samples. There is a clear proclivity for the psi grain-size distributions to be negatively skewed (exhibit a shift toward coarser fractions) and, to a lesser extent, to be platykurtic. Sachs (1982) provides percentiles for sampling distributions of α_3 and α_4. The box in Figure 6 encloses a region within which there is less than a 1 per cent chance that samples are non-normal. Only 12·5 per cent of the samples lie in this region. An alternative test for homoscedasticity is therefore desirable.

After comparing 56 tests, Conover *et al*. (1981) recommended the Brown–Forsythe test (Brown and Forsythe, 1974b) when samples are asymmetrical. Details of this test can be found in Brown and Forsythe (1974b) and Wilcox (1987). The procedure compares the variance of the spread of observations between samples (A) with that within samples (B) using an F-statistic. The spread of the observations is measured relative to the sample median rather than the mean, which renders the test more robust under non-normality. Results for the Pine and Sukunka Wolman samples are presented in Table I. In both cases, as suggested by $\Theta_s{}^2$ and $\Theta_p{}^2$, variances differ significantly between samples (note that N is very large, so F is very stringent).

We require an analysis of variance technique which is robust under heteroscedasticity, and not therefore based on F- tests. Welch (1951), James (1951), and Brown and Forsythe (1974a), among others, have developed tests for comparing sample means when sample variances are unequal. A simple precursor of these tests based on chi-square is appropriate in cases where sample sizes are large. Since average sample size is 388, the use of this test is appropriate here. Details are given in Appendix 1 and in James (1951) and Dijkstra (1988).

APPENDIX

Analysis of variance using chi-square (James, 1951; Dijkstra, 1988)

If there are $j=1$ to k samples, consisting of n_j observations, with mean grain size $\overline{\Psi}_j$, and variance s_j^2, then the null hypothesis of no difference between the population means, $H_0{:}\mu_1=\mu_2=.....=\mu_k$, is tested as follows:

$$C=\sum_{j=1}^{k} w_j\left(\overline{\psi}_j - x\right)^2$$

$$X=\frac{\sum_{j=1}^{k} w_j \overline{\Psi}_j}{W}$$

where

$$W=\sum_{j=1}^{k} w_j$$

$$W_j = n_j / s_j^{\,2}$$

If $C>\chi^2$ then reject H_0 and conclude that the means are significantly different. χ^2 is the $1-\alpha$ percentile of the chi-squared distribution with $k-1$ degrees of freedom.

Table III. Between-site variability. Equality of site means within each river

	Number of sites, k	W	X	C	$\chi^2_{(\alpha=0\cdot001)}$
Sukunka	90	47 703·84	5·703	9630·90	137·21
Pine	49	29 916·27	5·249	13 049·01	85·33

Where $C>\chi^2_{(\alpha)}$ reject H_0 of no significant difference ($\chi^2_{(\alpha)}$ is the $1-\alpha$ percentile of the χ^2 distribution with $k-1$ degrees of freedom)

Within-site, between-sample variability

This test was first applied to each of the six replicate suites to determine whether or not the mean grain size values of the individual samples vary significantly within sites (Table II). None of the replicate means are significantly different at $\alpha=0{\cdot}05$ and at only two sites (SBP 4 and SPB 7·5) are the means significantly different at $\alpha=0.10$. At PLH 5·75, PRD and STW 4b, differences remain insignificant for $\alpha=0{\cdot}50$. These results indicate that within-site variations are not significant.

Between-site variability

Finally, we address the question of whether there are significant grain-size variations between sites. The chi-square procedure was applied to the Pine and Sukunka data and results are presented in Table III. For both Pine and Sukunka Rivers C greatly exceeds $\chi^2_{0\cdot001}$, and there is no doubt that the mean grain sizes vary significantly between sites. This analysis provides the basis for exploring the question of whether grain size exhibits spatial structure.

IDENTIFICATION OF DISCONTINUITIES AND LATERAL SEDIMENT SOURCES

Previous studies are constrained by relatively few data or by consideration of a limited number of lateral sediment sources (Knighton, 1984, figure 3.10, p. 79; Church and Kellerhals, 1978, figure 7, p. 1157). In contrast,

there are a large number of potential sediment sources along both Pine and Sukunka Rivers and many samples were collected in order to facilitate identification of all significant lateral inputs.

Within a series of observations, one might model the value of an observed grain-size parameter Ψ, as

$$\Psi = \sum_i g_i * f_i(L_i) + e_w + e_b \tag{1}$$

where f_i is a function describing the cululative effects of fluvial abrasion and sorting processes working on material derived from significant source i; g_i is a weighting factor to express the contribution to the sediment mixture at the observing point of material from source i; L_i is distance downstream from source i to the observing point; e_w is a within-site error term for the specification of Ψ associated with the location of sample sites at bar scale; and e_B is a between-site (within-trend) error term associated with bar-to-bar variability (the formulation is partly due to C. Paola, pers. comm., 1997). Some further remarks must be made concerning this formulation. f_i may be specific to individual sources because it incorporates abrasion effects which depend on rock lithology and it incorporates sorting effects which may depend on input volume and physiographically constrained river channel characteristics downstream from the source. The weighting function g_i is related to the source strength and downstream transport of sediment from source i. It is also implicitly a function of L.

We lack most of the information about source characteristics to test this model. At this stage, in fact, we are uncertain which are the significant sources. To make progress in studying the effect of lateral sources, we replace the sum with a simple empirical function which defines grain-size trends between successive sources:

$$\Psi = f(L_i) + e_w + e_b \tag{1a}$$

wherein the two error terms are supposed to be normally distributed random variables (for Ψ measure) and, in the absence of additional sediment inputs, $e_w + e_b$ account for the total residual variance about an empirical relation between grain size and distance.

Our initial problem now is to take an unclassified sequence of data and identify those between-site variations that are caused by intervening lateral sediment sources, rather than by sampling errors, inherent between-site variation, or distance. Where a lateral source does provide a likely explanation, one must then determine whether it has a transient or persistent effect on bed material texture, that is whether it resets $f(L)$.

Distinguishing among causes of between-site variation

Distinguishing among the possible causes of a between-site difference is not straightforward. Only the within-site error term (e_w) can be quantified *a priori* (using replicate samples). An estimate of inherent between-site variability (e_b), might be obtained by considering variations between closely spaced bars along input-free reaches. However, along these rivers, where bar spacings typically range between 10^2 and 10^3 m, one cannot assume that samples from consecutive bars are unaffected by distance. The magnitude of the distance effect cannot be defined prior to the determination of ($f(L_i)$), and is therefore unknown until discontinuities are identified.

The problem is simplified if one assumes that discontinuities tend to be positive, such that $\Psi_D - \Psi_U > 0$, where Ψ_D is the value of a grain-size parameter and Ψ_U is the value of the parameter at that site immediately upstream. If the volume of an influx of relatively fine sediment is sufficiently large, a step decrease in grain size is possible. Anthropogenic inputs are responsible for such changes on the East Fork River, Wyoming (Andrews, 1979) and on Ringarooma River, Tasmania (Knighton, 1989). Sambrook Smith and Ferguson (1995) highlight the role of the Drumheller Badlands in instigating a gravel–sand transition on the Red Deer River, Alberta. However, unless a fine input is voluminous enough to have a lasting effect on main stem competence and capacity (Rhoads, 1989), it is less likely to persist than a relatively coarse input, because the relative coarseness of the mainstem is indicative of a transport regime capable of removing the finer material. It is therefore reasonable to focus on downstream increases in size when searching for discontinuities. If one also assumes that sorting and

abrasion processes tend to produce a downstream reduction in gross grain-size parameters, then by focusing on positive changes one is also excluding distance as a potential cause of observed between-site differences. Frostick and Reid (1980) have shown that this is not necessarily true for individual lithologies, but the great majority of empirical evidence indicates that downstream fining is the norm in alluvial systems.

Individual samples provide estimates of the Ψ_{50} and Ψ_{95} at a site, and standard errors can be defined using replicate samples. In cases where a positive downstream change is identified, a *t*-test can be used to establish whether the difference in the value of a given parameter between consecutive sampling sites exceeds that expected on the basis of sampling chance. Pairs flagged by this test provide a starting point for further investigation.

Within-site variance estimates are required for both percentiles (*p*). For an individual Wolman sample the standard errors, σ_{Wp}, are approximated using the best estimate of within-site variance based on the six sets of replicate samples. For the photographic estimates the within-site error, σ_{Pp}, incorporates the variance due to site selection (σ_{Wp}) and the mean standard error associated with the prediction of an individual observation. In making a comparison of consecutive Ψ_{50} or Ψ_{95} values a *t*-value is calculated as:

$$t = \frac{\Psi_{pD} - \Psi_{pU}}{\sqrt{\sigma_{pD}^{2} + \sigma_{pU}^{2}}} \tag{2}$$

where subscript D refers to the downstream sample and U to the upstream sample. Appropriate standard error estimates (σ_{Wp}, σ_{Pp}) are substituted for σ_{pD} and σ_{pU} depending on the technique used at the sampling site, and the relevant degrees of freedom are calculated in the usual way.

Between 21 sites along the Pine and 19 along the Sukunka, positive changes in both Ψ_{50} and Ψ_{95} exceed those associated with within-site variance with a probability of more than 95 per cent (one-tailed *t*-test, $\alpha = 0{\cdot}05$). At an additional two sites on the Pine and 10 sites on Sukunka either Ψ_{50} or Ψ_{95} exceed within-site variance with a probability of more than 95 per cent. These pairs of sites represent between-site changes which are unlikely to be the result of distance or sampling effects. Significant steps in Ψ_{50} are indicated by solid circles (at the downstream site) in Figures 7 and 8.

It remains to distinguish inherent between-site variability from lateral source effects. The association of the latter with potential sediment sources (tributaries and streamside outcrops of non-alluvial material) makes this possible. All tributaries and non-alluvial contacts are considered to be potential sources of sediment. For each significant between-site difference identified, potential sources of sediment in the intervening reach were assessed. Non-alluvial materials and/or tributaries which currently supply or may have recently supplied sediment are present in all but five cases along the Sukunka and one on the Pine. In the absence of reasonable exogenous explanations, these six steps are supposed to reflect inherent between-site variability within alluvial reaches.

Significant lateral inputs and sedimentary links

The effect on bed material texture of a given lateral source depends on the delivery rate and textural characteristics of the material supplied. Redefinition of the throughput population is dependent upon an influx that is sufficiently voluminous or which exhibits a decidedly dissimilar grain-size distribution. Consequently, not all of the sources identified above have a persistent effect on bed material texture. Those which do can be identified by their association with the beginning and/or end of a reasonably systematic fining trend. Those which do not are presumably sufficiently small and/or texturally similar as to be accommodated by the throughput population within a few channel widths. The former sources define a series of texturally distinct reaches which provide a meaningful framework for examining textural change along the mainstem. The smaller inputs simply augment residual variability due to within- and between-site variance.

The identification of significant lateral sources is thus dependent on the identification of fining trends and *vice versa*. In light of the scatter which exists in most reaches and the large number of potential sediment sources, recognizing trends is seldom straightforward and a significant degree of judgement is usually required. An absence of grain-size data because of access problems further complicates the task in some reaches.

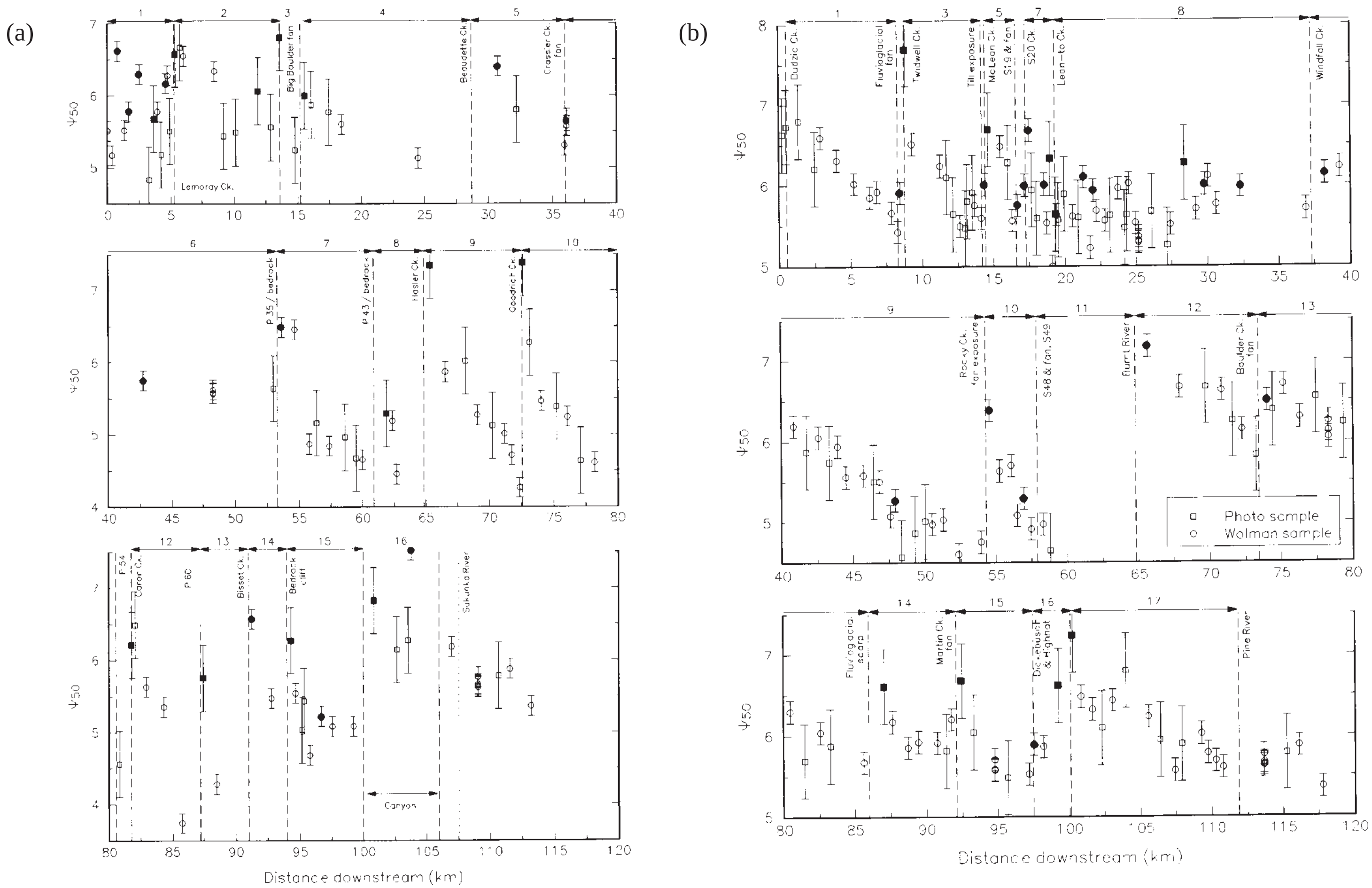

Figure 7. Downstream variation of Ψ_{50} along (a) Pine River and (b) Sukunka River. Significant between-site steps (downstream site is solid) and sedimentary links are indicated. Error bars are 95 per cent confidence intervals.

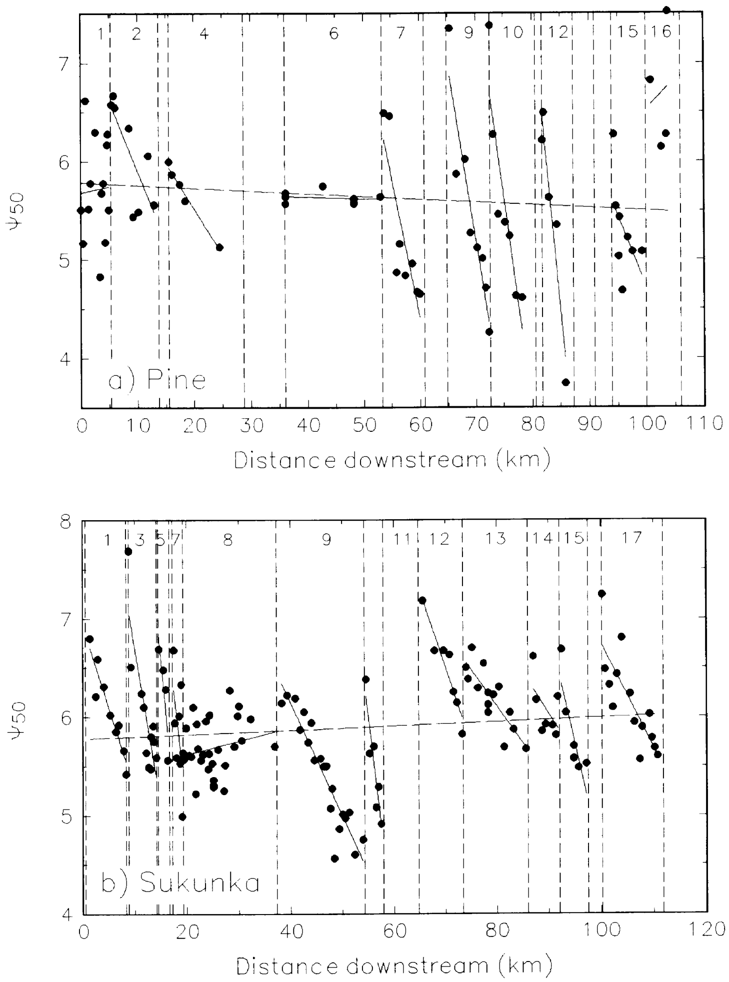

Figure 8. Exponential regression models fitted to the entire Ψ_{50} data sets (long dash) and to individual sedimentary links (solid) for (a) Pine River and (b) Sukunka River. Sedimentary links are numbered and discontinuities are indicated by dashed vertical lines

Evaluation of the potential sediment sources in terms of their sediment delivery capabilities is fundamental in order to decide whether or not a given source can reasonably explain a coincident step. Field observations were used to inform these decisions.

In total, 17 discrete reaches along Sukunka River and 16 reaches along Pine River have been defined. These are indicated with the associated discontinuities and significant between-site steps in Figure 7, which shows downstream changes in Ψ_{50}. The presence or absence of significant between-site steps in Ψ_{95} aided in the delineation of these reaches (Rice, 1996), but to maintain clarity Ψ_{95} data are not shown. The reaches are demarcated upstream and/or downstream by between-site, downstream increases in grain size that are reasonably explained by coincident lateral sediment sources. In most cases they exhibit fining trends of variable strength, within which scatter about a relation with distance is attributable to site- and bar-scale variability, the latter incorporating lateral effects which are insufficient to redefine mainstem texture. We refer to such reaches as *sedimentary links*. Our interpretations are not the only ones possible, but we have been consistent in our attempt to distinguish among possible sources of variance on a site-by-site basis. In several links almost 90 per cent of exposed bars were sampled and on average 63 per cent of bars on the Sukunka and 51 per cent on the Pine were sampled. Difficulties of interpretation reflect the complexity of the system rather than an inability to characterize it.

Table IV. Pine River sedimentary links

Link	Upstream lateral sediment source	Length (km)	No. samples	Comments	Ψ_{50} SS residual	Ψ_{50} R^2	Ψ_{95} SS residual	Ψ_{95} R^2
1	unspecified	–	13	no fining, fan and glaciofluvial inputs	3·18	0·00	3·44	0·00
2	Lemoray Ck	8·4	8	weak fining	0·75	0·61	0·74	0·55
3	Upper Big Boulder Ck	1·5	2	very short, few data	–	–	–	–
4	Lower Big Boulder Ck	13·5	5	fining	0·01	0·98	0·00	0·99
5	Beaudette Ck	7·3	3	fining	–	–	–	–
6	Fan (Crassier Ck)	17·3	8	few data (four sites), assessment reserved	0·03	0·04	0·05	0·58
7	Tributary P35/bedrock	7·6	8	fining	1·16	0·72	1·19	0·69
8	Tributary P43/bedrock	3·9	3	few data, assessment reserved	–	–	–	–
9	Hasler Ck	7·8	8	strong fining	0·75	0·88	0·87	0·88
10	Goodrich Ck	7·9	7	strong fining	1·07	0·81	1·38	0·78
11	Tributary P54	1·2	1	very short, few data	–	–	–	–
12	Caron Ck	5·5	5	strong fining	0·39	0·92	0·47	0·92
13	Tributary P60	3·8	2	few data but strong fining observed	–	–	–	–
14	Bisset Ck	3·0	2	few data but strong fining observed	–	–	–	–
15	Bedrock cliff	6·0	8	weak fining	1·17	0·26	1·83	0·66
16	Canyon/bedrock	7·5	4	canyon lag materials	1·16	0·02	2·06	0·06
				Sum of residuals and average R^2 for 10 individual models	**9·81**	0·52	**12·03**	0·61
				Residual sum of squares and R^2 for single model for same 74 data	**37·10**	0·02	**46·78**	0·03

The final four columns detail the improvement in residual variation following classification of grain-size data by sedimentary links. Exponential models relating Ψ_{50} and Ψ_{95} to distance downstream (km) were used in this comparison. Sections with fewer than four data points were excluded from the analysis. Significant fining trends are not apparent in the Canyon (link 16) or the reach upstream of Lemoray Creek (link 1) and sampling resolution is relatively low downstream of Crassier Creek (link 6)

Table V. Sukunka River sedimentary links

Link	Upstream lateral sediment source	Length (km)	No. samples	Comments	Ψ_{50} SS residual	Ψ_{50} R^2	Ψ_{95} SS residual	Ψ_{95} R^2
1	Dudzic Ck	7·8	9	strong fining	0·16	0·89	0·22	0·73
2	Fluvioglacial fan	0·5	1	very short, few data	–	–	–	–
3	Twidwell Ck	5·4	11	fining	1·13	0·79	0·99	0·78
4	Till exposure	0·2	1	very short, few data	–	–	–	–
5	McLean Ck	2·2	4	fining	0·19	0·73	0·10	0·73
6	Tributary S19	0·7	2	very short, few data	–	–	–	–
7	Tributary S20	2·0	7	weak fining	1·33	0·29	0·93	0·23
8	Lean-to Ck	18·0	30	no fining	2·05	0·04	2·22	0·02
9	Windfall Ck	17·0	20	strong fining	0·78	0·86	0·48	0·92
10	Fan (Rocky Ck)	3·6	6	strong fining	0·22	0·84	0·08	0·95
11	Tributary S48/S49	6·9	2	few data, assessment reserved	–	–	–	–
12	Burnt River	8·6	7	strong fining	0·14	0·88	0·11	0·93
13	Fan (Boulder Ck)	12·6	14	fining	0·36	0·70	0·25	0·80
14	Fluvioglacial scarp	6·1	7	fining	0·34	0·30	0·52	0·23
15	Fan (Martin Ck)	5·4	7	fining	0·32	0·71	0·36	0·68
16	Dickebusch Ck and fan	2·7	3	few data, downstream coarsening	–	–	–	–
17	Highhat Ck and fan	11·6	14	fining	1·02	0·66	1·05	0·66
				Sum of residuals and average R^2 for 12 individual models	**8·04**	0·65	**7·31**	0·64
				Residual sum of squares and R^2 for single model for same 136 data	**36·22**	0·02	**39·00**	0·00

The final four columns detail the improvement in residual variation following classification of grain-size data by sedimentary links. Exponential models relating Ψ_{50} and Ψ_{95} to distance downstream (km) were used in this comparison. Sections with fewer than four data points were excluded from the analysis. Significant fining trends are not apparent in the link downstream of Lean-to Creek (link 8)

Tables IV and V provide brief information about each of the 33 links identified. The 16 Pine links are associated with 16 significant lateral sources (the upstream limit of link 1 remains unspecified). Of these, 13 are tributaries (including Sukunka River), one is an active Holocene fan exposure, and two are bedrock controlled (in addition, two of the tributary sources are coincident with bedrock cliffs). Of 18 significant lateral sources on Sukunka River, 12 are tributaries (including Pine River), three are active Holocene fan exposures, two are active glaciofluvial exposures, and one is an active till exposure. Downstream fining trends are apparent in 21 of the 33 links, though in three of the outstanding 12, sampling resolution is too low to allow a reasonable assessment, and a further five are very short with only one or two sediment accumulations (they lack sufficient distance to develop systematic fluvial effects). In two sections (upstream of Lemoray Creek on the Pine, and between Lean-to Creek and Windfall on the Sukunka) no trends are apparent, and in the link adjacent to Dickebusch and Highhat fans, downstream coarsening occurs. The Canyon section of Pine River (reach 16) is a special case in that the bed is a lag deposit which sequesters little mobile sediment. Fining trends delimited by tributary junctions thus dominate the pattern of textural change.

DISCUSSION

Improvement in explanation

Categorization of grain-size parameters according to the sedimentary links in which they are located greatly reduces unexplained textural variability on both rivers. This is clear when one compares the total residual variance about a single regression model with that associated with a set of models fitted to the individual reaches. Exponential models, which have been widely utilized in studies of textural change, are used to make this comparison. For psi data the relation takes the linear form:

$$\Psi = \Psi_0 + \alpha L \tag{3}$$

where Ψ_0 is the value of Ψ at $L = 0$ (here, at the lateral source which initiates a link), and α is a coefficient of diminution.

Results for Pine and Sukunka are presented in Tables IV and V. Links which include less than four data points were excluded from the analysis. For Pine River, the use of link-scale models reduces the total residual sum of squares by 74 per cent for both Ψ_{50} and Ψ_{95} relations. For Sukunka River there are similar reductions in residual variance of 78 per cent for Ψ_{50} and 81 per cent for Ψ_{95}. Exponential models of the relations between distance and Ψ_{50} are shown in Figure 8.

Implications for modelling

These results provide thorough confirmation that explanation of textural change in alluvial systems is dependent on identifying significant lateral sources. This is certainly the case at scales on the order of 10^0 to 10^2 km. At larger scales (10^3 to 10^4 km) the link-scale variability identified here may be attenuated (especially in extensive sedimentary basins dominated by fine gravel and sand) and apparent simplicity may re-emerge in the form of a consistent fining gradient. Models of fluvial deposition within major sedimentary basins incorporate this assumption (Paola *et al*., 1992; Robinson and Slingerland, 1998) and it yields reasonable results in comparison with observed textural trends in major bodies of terrestrial clastic sediments. Nonetheless, the pattern of punctuated fining is apt to be important in a wide range of geomorphological, ecological and engineering applications.

In the sense that significant lateral sources represent points of adjustment within the sedimentary system, an analogy can be drawn with tributary junctions in the channel network. Adjustment is to an input of clastic material rather than an input of water and, by extension, the intervening sedimentary links are analogous (and are often equivalent) to channel network links. Within a majority of links, fluvial processes operate relatively free of lateral interruptions, just as network links are supposed not to have significant hydrologic inputs. The sedimentary link thereby isolates variation due to fluvial fining processes and provides the fundamental natural

unit within which fining models can be tested and developed. In testing their fining model on the Allt Dubhaig, Scotland, Hoey and Ferguson (1994) emphasized this requirement by selecting a short reach with a single upstream sediment source.

A network of sedimentary links is delimited by the multiplicity of lateral sediment sources that characterize any fluvial system. These include the network of channels, coupled landforms, and persistent palaeodeposits. Given the significant advances in physically realistic fining models that have recently been achieved (Parker, 1991; Hoey and Ferguson, 1994; Paola and Seal, 1995; Cui *et al*., 1996), progress in modelling fluvial sedimentary systems might now benefit from the wider spatial and longer temporal geomorphological perspective which delineation of a network of sedimentary links provides. It is not our intention to imply that existing models of fining processes are in any way inappropriate. On the contrary, we suggest that sedimentary links provide a framework within which modelling endeavours might usefully proceed.

The successful identification of discontinuities and sedimentary links on Pine and Sukunka Rivers is not surprising given that grain-size data were at hand. However, in order to apply fining models in a predictive mode, it will be necessary to identify significant lateral sediment sources *a priori* and this is the subject of a forthcoming paper. It will then be necessary, further, to find means to characterize these sources as to strength (sediment yield) and sediment character.

CONCLUSION

Statistical analysis of a high-resolution grain-size data set is accomplished using a chi-squared statistic capable of accommodating the heteroscedasticity of observed grain-size distributions. Because of general non-normality, heteroscedasticity is confirmed using the Brown–Forsythe test rather than the standard Bartlett test. Within-site, between-sample variability is not significant, while between-site variations are significant for both rivers. These results provide a basis for examining the spatial pattern of grain-size change.

Data from both rivers demonstrate the substantial improvement in statistical explanatory power afforded by classifying the rivers into a series of discrete links separated by significant lateral sediment sources. Most of these links exhibit fining trends which reflect the modification of material by fluvial processes in the absence of distruption by major lateral inputs.

An important implication for models of textural change is that models of downstream fining in rivers with lateral sources can only be as successful as the isolation of those sources and thereby the links within which fining processes operate unhindered. The concept of the *sedimentary link* is introduced as a means of isolating fluvial maturation and lateral inputs, and provides a framework for modelling textural change at the basin scale.

Shaw and Kellerhals (1982) noted a high degree of variability and general downstream coarsening in the mountainous portions of several Albertan gravel-bed rivers. Examination of the undifferentiated grain-size data for Sukunka and Pine Rivers (located in the same major physiographic province as the Albertan rivers) supports their observation. They suggest that ‘an explanation for these observations lies in the complex historical and present-day geomorphological processes in these reaches’ (Shaw and Kellerhals, 1982, p. 48), and the analysis presented here confirms that this is indeed the case. Careful examination of tributaries and other lateral sources, with an eye to the recent past, has revealed a reasonable pattern of textural changes that initially appear unstructured.

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REFERENCES

Andrews, E. D. 1979. 'Hydraulic adjustment of the East Fork River, Wyoming to the supply of sediment', in Rhodes, D. D. and Williams, G. P. (Eds), *Adjustments of the Fluvial System*, Allen and Unwin, London, 69–94.

Bartlett, M. S. 1937. 'Properties of sufficiency and statistical tests', *Proceedings of the Royal Society, Series A*, **160**, 268–282.

Bluck, B. J. 1971. 'Sedimentation in the meandering River Endrick', *Scottish Journal of Geology*, **7**, 93–138.

Bluck, B. J. 1982. 'Texture of gravel bars in braided streams', in Hey, R. D. *et al*. (Eds), *Gravel Bed Rivers*, John Wiley and Sons, Chichester, 339–355.

Box, G. E. P. 1953. 'Non-normality and tests on variances', *Biometrika*, **40**, 318–335.

Box, G. E. P. 1954. 'Some theorems on quadratic forms applied in the study of analysis of variance problems, I. Effect of inequality of variance in the one-way classification', *Annals of Mathematical Statistics*, **25**, 290–302.

Bradley, W. C. 1970. 'Effect of weathering on abrasion of granitic gravel, Colorado River (Texas)', *Geological Society of America Bulletin*, **81**, 61–80.

Bradley, W. C., Fahnstock, R. K. and Rowekamp, E. T. 1972. 'Coarse sediment transport by flood flows on Knik River, Alaska', *Geological Society of America Bulletin*, **83**, 1261–1284.

Brewer, P. A. and Lewin, J. 1993. *In-transport modification of alluvial sediment: field evidence and laboratory experiments*, International Association of Sedimentologists Special Publication, **17**, 23–35.

Brierley, G. J. and Hickin, E. J. 1985. 'The downstream gradation of particle sizes in the Squamish River, British Columbia', *Earth Surface Processes and Landforms*, **10**, 597–606.

Brown, M. B. and Forsythe, A. B. 1974a. 'The small sample behaviour of some statistics which test the equality of several means', *Technometrics*, **16**, 129–132.

Brown, M. B. and Forsythe, A. B. 1974b. 'Robust test for the equality of variances', *Journal of the American Statistical Association*, **69**, 364–367.

Brush, L. M. 1961. *Drainage basins, channels, and flow characteristics of selected streams in Central Pennsylvania*, United States Geological Survey Professional Paper **282-F**, 145–181.

Church, M. and Kellerhals, R. 1978. 'On the statistics of grain size variation along a gravel river', *Canadian Journal of Earth Science*, **15**, 1151–1160.

Church, M. A., McLean, D. G. and Wolcott, J. F. 1987. 'River bed gravels: sampling and analysis', in Thorne, C. R., Bathurst, J. C. and Hey, R. D. (Eds), *Sediment Transport in Gravel-Bed Rivers*, John Wiley and Sons, Chichester, 43–48.

Cliff, A. D. and Ord, J. K. 1981. *Spatial Processes: Models and Applications*, Pion, London, 266 pp.

Conover, W. J., Johnson, M. E. and Johnson, M. M. 1981. 'A comparative study for homogeneity of variances, with applications to the Outer Continental Shelf bidding data', *Technometrics*, **23**, 351–361.

Cui, Y., Parker, G. and Paola, C. 1996. 'Numerical simulation of aggradation and downstream fining', *Journal of Hydraulic Research*, **34**, 185–204.

Dawson, M. 1982. *Sediment variation in a braided reach of the Sunwapta River, Alberta*, unpublished MSc thesis, University of Alberta, 186 pp.

Dawson, M. 1988. 'Sediment size variation in a braided reach of the Sunwapta River, Alberta, Canada', *Earth Surface Processes and Landforms*, **13**, 599–618.

Dijkstra, J. B. 1988. 'Analysis of means in some non-standard situations', *Centrum voor Wiskunde en Informatica*, Tract **47**, 138 pp.

Diplas, P. and Sutherland, A. J. 1988. 'Sampling techniques for gravel sized sediments', *American Society of Civil Engineers, Journal of the Hydraulics Division*, **114**, 484–501.

Ferguson, R. I., Hoey, T., Wathen, S. and Werrity, A. 1996. 'Field evidence for rapid downstream fining of river gravels through selective transport', *Geology*, **24**, 179–182.

Fripp, J. B. and Diplas, P. 1993. 'Surface sampling in gravel streams', *American Society of Civil Engineers, Journal of Hydraulic Engineering*, **119**, 473–490.

Frostick, L. E. and Reid, I. 1980. 'Sorting mechanisms in coarse-grained alluvial sediments: fresh evidence from a basalt plateau gravel, Kenya', *Journal of the Geological Society of London*, **137**, 431–441.

Hey, R. D. and Thorne, C. R. 1983. 'Accuracy of surface samples from gravel bed material', *American Society of Civil Engineers, Journal of Hydraulic Engineering*, **109**, 842–851.

Hoey, T. B. and Ferguson, R. I. 1994. 'Numerical simulation of downstream fining by selective transport in gravel-bed rivers: model development and illustration', *Water Resources Research*, **30**, 2251–2260.

Huddart, D. 1994. 'Rock-type controls on downstream changes in clast parameters in sandur systems in southeast Iceland', *Journal of Sedimentary Research*, **A64**, 215–225.

Ichim, I. and Radoane, M. 1990. 'Channel sediment variability along a river: a case study of the Siret River (Romania)', *Earth Surface Processes and Landforms*, **15**, 211–225.

James, G. S. 1951. 'The comparison of several groups of observations when the ratios of the population variances are unknown', *Biometrika*, **38**, 324–329.

Keller, E. A. 1971. 'Areal sorting of bed-load material: the hypothesis of velocity reversal', *Geological Society of America Bulletin*, **82**, 753–756.

Knighton, A. D. 1980. 'Longitudinal changes in size and sorting of stream bed material in four English Rivers', *Geological Society of America Bulletin*, **91**, 55–62.

Knighton, A. D. 1984. *Fluvial Forms and Processes*, Edward Arnold, London, 218 pp.

Knighton, A. D. 1989. 'River adjustment to changes in sediment load: the effects of tin mining on the Ringarooma River, Tasmania, 1875–1984', *Earth Surface Processes and Landforms*, **14**, 333–359.

Kodama, Y. 1994. 'Downstream changes in the lithology and grain size of fluvial gravels, the Watarase River, Japan: evidence of the role of abrasion in downstream fining', *Journal of Sedimentary Research*, **A64**, 68–75.

Krumbein, W. C. 1942. 'Flood deposits of the Arroyo Seco, Los Angeles County, California', *Geological Society of America Bulletin*, **53**, 1355–1402.

Kuenen, P. H. 1956. 'Experimental abrasion of pebbles: 2. Rolling by current', *Journal of Geology*, **64**, 336–368.
Mackin, J. H. 1948. 'Concept of the graded river', *Bulletin of the Geological Society of America,* **59**, 463–512.
Mayer, L., Gerson, R. and Bull, W. B. 1984. 'Alluvial gravel production and deposition: a useful indicator of Quaternary climatic changes in deserts (a case study in southwestern Arizona)', in Schick, A. P. (Ed.) *Channel Processes – Water, Sediment, Catchment Controls, Catena Supplement,* **5**, 137–151.
Miller, J. P. 1958. *High mountain streams: effects of geology on channel characteristics and bed material*, State Bureau of Mines and Mineral Resources, Memoir 4, New Mexico Institute of Mining and Technology, Socorro, New Mexico, 53 pp.
Milne, J. A. 1982. 'Bed-material size and the riffle–pool sequence', *Sedimentology,* **29**, 267–278.
Mosley, M. P. and Tindale, D. S. 1985. 'Sediment variability and bed material sampling in gravel-bed rivers', *Earth Surface Processes and Landforms,* **10**, 465–482.
Paola, C. and Seal, R. 1995. 'Grain size patchiness as a cause of selective deposition and downstream fining', *Water Resources Research,* **31**, 1395–1407.
Paola, C., Heller, P. L. and Angevine, C. L. 1992. 'The large scale dynamics of grain-size variation in alluvial basins, 1: Theory', *Basin Research,* **4**, 73–90.
Parker, G. 1991. 'Selective sorting and abrasion of river gravel, I, theory', *Journal of Hydraulic Engineering,* **117**, 131–149.
Parker, G. and Andrews, E. D. 1985. 'Sorting of bedload sediment by flow in meander bends', *Water Resources Research,* **21**, 1361–1373.
Penning-Rowsell, E. and Townshend, J. R. G. 1978. 'The influence of scale on the factors affecting stream channel slope', *Institute of British Geographers Transactions,* **3**, 395–415.
Pizutto, J. E. 1992. 'The morphology of graded rivers: a network perspective', *Geomorphology,* **5**, 457–474.
Pizutto, J. E. 1995. 'Downstream fining in a network of gravel-bedded rivers', *Water Resources Research,* **31**, 753–759.
Rhoads, B. L. 1989. 'Longitudinal variations in the size and sorting of bed material along six arid-region mountain streams', *Catena Supplement,* **14**, 87–105.
Rice, S. P. 1996. *Bed Material Texture Along Gravel Bed Rivers With Confluences*, unpublished PhD thesis, University of British Columbia, Canada, 238 pp.
Rice, S. P. and Church, M. 1996a. 'Bed material texture in low order streams on the Queen Charlotte Islands, British Columbia', *Earth Surface Processes and Landforms,* **21**, 1–18.
Rice, S. P. and Church, M. 1996b. 'Sampling surficial fluvial gravels: the precision of size distribution percentile estimates', *Journal of Sedimentary Research,* **66**, 654–665.
Robinson, R. A. J. and Slingerland, R. L. (1998) 'Origin of fluvial grain-size trends in a foreland basin: the Pocono Formation of the Central Appalachian Basin', *Journal of Sedimentary Research*, 68.
Russell, R. D. 1939. 'Effects of transportation on sedimentary particles', in Trask, P. D. (Ed.), *Recent Marine Sediments*, American Association of Petroleum Geologists, Tulsa, 33–47.
Sachs, L. 1982. *Applied Statistics: a Handbook of Techniques*, Springer-Verlag, Berlin, 706 pp.
Sambrook Smith, G. H. and Ferguson, R. I. 1995. 'The gravel–sand transition along river channels', *Journal of Sedimentary Research,* **A65**, 423–430.
Schlee, J. 1957. 'Upland gravels of southern Maryland', *Bulletin of the Geological Society of America,* **68**, 1371–1410.
Shaw, J. and Kellerhals, R. 1982. *The Composition of Recent Alluvial Gravels in Alberta River Beds*, Alberta Research Council, Edmonton, Bulletin **41**, 151 pp.
Smith, N. D. 1974. 'Sedimentology and bar formation in the Upper Kicking Horse River, a braided outwash stream', *Journal of Geology,* **82**, 205–223.
Stelczer, K. 1981. *Bed-load Transport, Theory and Practice*, Water Resources Publications, Littleton, Colorado, 295 pp.
Sternberg, H. 1875. 'Untersuchungen Über Längen-und Querprofil geschiebeführender Flüsse', *Zeitschrift für Bauwesen*, **XXV**, 483–506.
Tan, W. 1982. 'Sampling distributions and robustness of t, F and variance ratio in two samples and ANOVA models with respect to departure from normality', *Communications in Statistics – Theory and Methods,* **11**, 2485–2511.
Troutman, B. M. 1980. 'A stochastic model for particle sorting and related phenomena', *Water Resources Research,* **16**, 65–76.
Welch, B. L. 1951. 'On the comparison of several mean values an alternative approach', *Biometrika,* **38**, 330–336.
Werritty, A. 1992. 'Downstream fining in a gravel bed river in Southern Poland: lithological controls and the role of abrasion', in Billi, P. *et al*. (Eds), *Dynamics of Gravel Bed Rivers,* Wiley, Chichester, 333–346.
Wilcox, R. R. 1987. *New Statistical Procedures for the Social Sciences: Modern Solutions to Basic Problems*, Lawrence Erlbaum Associates, Hillside, New Jersey, 423 pp.
Wolcott, J. and Church, M. 1991. 'Strategies for sampling spatially heterogeneous phenomena: the example of river gravels', *Journal of Sedimentary Petrology,* **61**, 834–843.
Wolman, M. G. 1954. 'A method for sampling coarse river-bed material', *American Geophysical Union Transactions,* **35**, 951–956.

